Di-Higgs observation as a probe of Higgs self-coupling

Amit Adhikary

Indian Institute of Science, Bengaluru, India

Based on

JHEP 07 (2018) 116, with S. Banerjee, R.K. Barman, B. Bhattacherjee and S. Niyogi

JHEP 12 (2020) 179, with R.K. Barman and B. Bhattacherjee

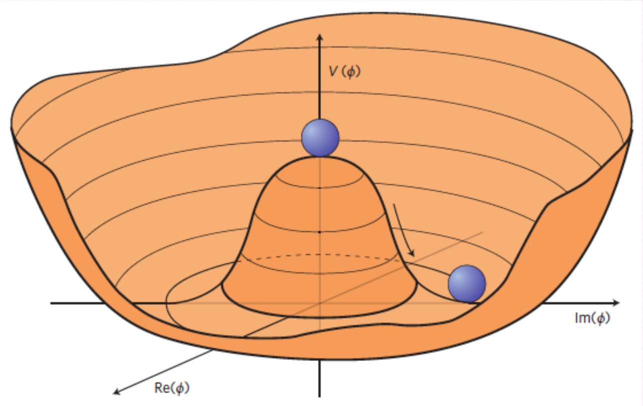
DPF 2021, 12-14 July, 2021, Online

Introduction

Higgs boson has been discovered at the Large Hadron Collider (LHC) in 2012 which is more or less consistent with the Standard Model (SM) Higgs boson. The coupling of Higgs boson to gauge bosons and fermions are being measured with increasing precision at the experiment. There is no direct measurement of Higgs self-coupling till now.

The scalar potential:

$$V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$ ← completely arbitrary choice →



The only way to reconstruct this potential is by knowing the exact value of λ .

In the SM, with Higgs boson mass of 125 GeV, $\lambda_{SM} = \dfrac{{m_h}^2}{2v^2} \sim 0.13$.

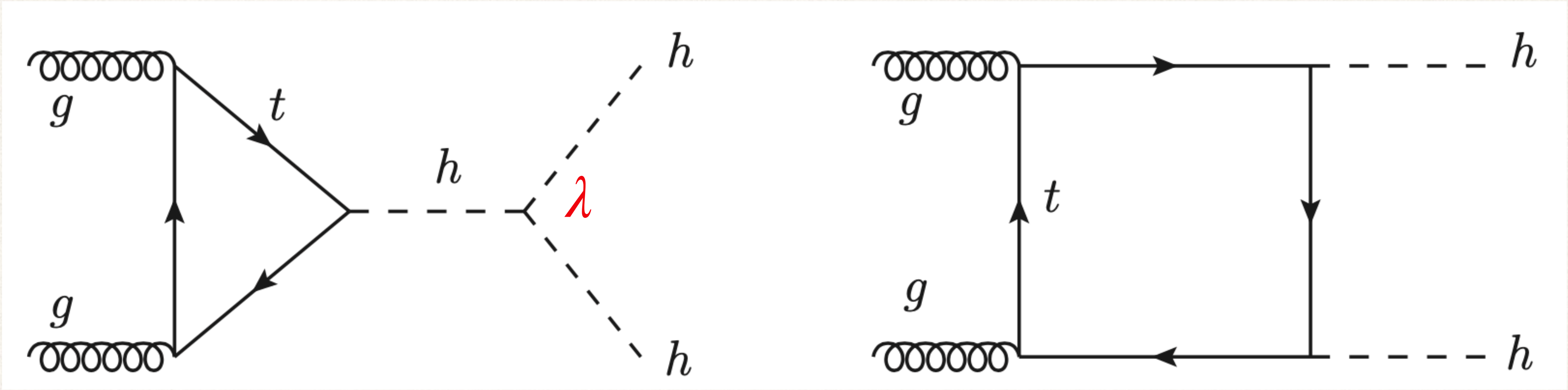
Q. Is this the value of Higgs boson self coupling for the spontaneous symmetry breaking mechanism (SSB)?

Ans. A direct measurement is necessary at the collider.

Motivation: Higgs self-coupling and Higgs pair production

A direct probe of Higgs self coupling, λ is to produce two Higgs boson from one Higgs boson, called (non-resonant) Higgs pair production or di-Higgs production, $pp \rightarrow hh$.

Dominant production mode at hadron collider: gluon gluon fusion, $gg \rightarrow hh$.



Triangle diagram

Box diagram

Challenging Task:

Cancellation between triangle and box diagrams → very small production cross-section.

Di-Higgs production at HL-LHC

HL-LHC: $\sqrt{s} = 14$ TeV and 3 ab^{-1} of integrated luminosity, $\sigma(gg \to hh) = 36.69$ fb [CERN Twiki].

Channels are chosen based on their production rate and cleanliness.

The selected 11 possible final states are,

- $b\bar{b}\gamma\gamma$
- $b\bar{b}\tau\tau \to (a)\ \tau_h\tau_h$, $(b)\ \tau_h\tau_\ell$ and $(c)\ \tau_\ell\tau_\ell$
- $b\bar{b}WW^* \to (a)\ b\bar{b}\ell jj + \not{E}_T$ and $(b)\ b\bar{b}\ell\ell + \not{E}_T$
- $WW^*\gamma\gamma \to (a)\ \ell jj\gamma\gamma + \not{E}_T$ and $(b)\ \ell\ell\gamma\gamma + \not{E}_T$
- $WW^*WW^* \to (a)\ 2\ell 4j + \not{E}_T$, $(b)\ 3\ell 2j + \not{E}_T$ and $(c)\ 4\ell + \not{E}_T$

Standard cut-based analysis (Follow CMS/ATLAS analysis whenever available).

Multivariate analysis using Boosted Decision Tree (BDT) algorithm.

The $b\bar{b}\gamma\gamma$ channel

- $pp \to hh \to b\bar{b}\gamma\gamma$: Clean channel but low production rate
- Major backgrounds: $b\bar{b}\gamma\gamma$, $t\bar{t}h$, $b\bar{b}h$, Zh
- Fake backgrounds: $c\bar{c}\gamma\gamma$, $jj\gamma\gamma$, $b\bar{b}j\gamma$, $c\bar{c}j\gamma$, $b\bar{b}jj$

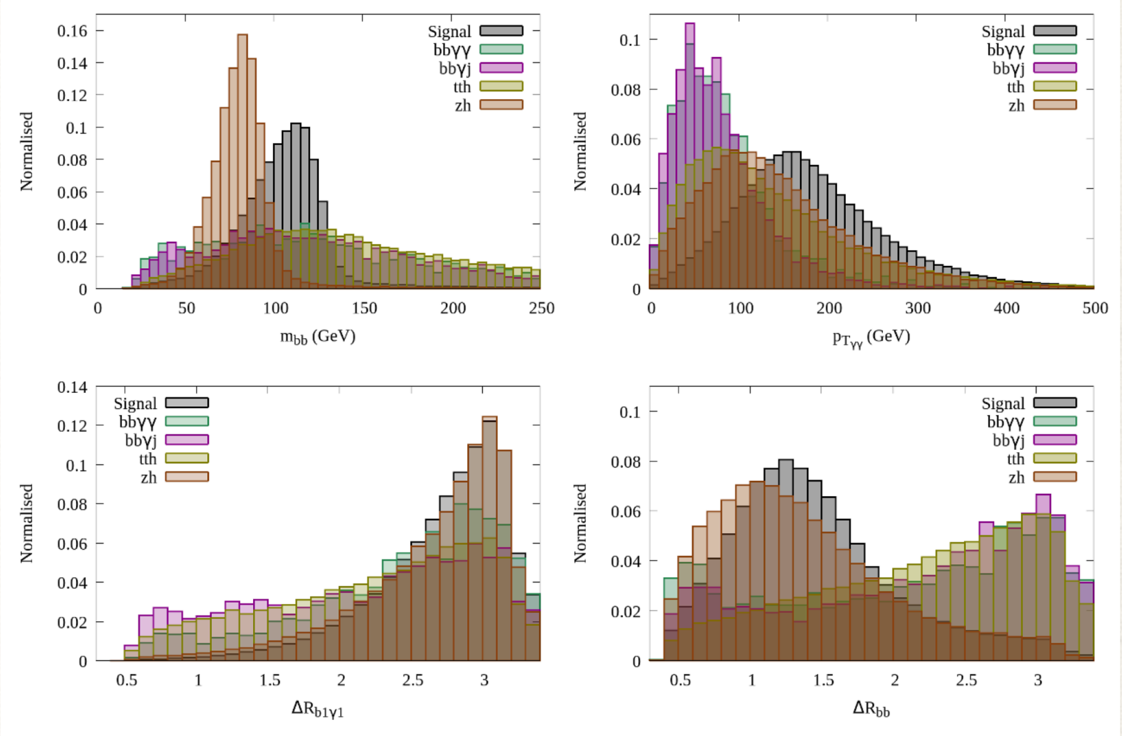


Fig. Normalised distributions of m_{bb}, $p_{T,\gamma\gamma}$, $\Delta R_{b1\gamma 1}$, ΔR_{bb}.

Cut-based Analysis

Selection cuts
$N_j < 6$
$0.4 < \Delta R_{\gamma\gamma} < 2.0,\ 0.4 < \Delta R_{bb} < 2.0,\ \Delta R_{\gamma b} > 0.4$
$100\,\text{GeV} < m_{bb} < 150\,\text{GeV}$
$122\,\text{GeV} < m_{\gamma\gamma} < 128\,\text{GeV}$
$p_{T,bb} > 80\,\text{GeV},\ p_{T,\gamma\gamma} > 80\,\text{GeV}$

Signal Significance, $S/\sqrt{B}$ = 1.46

BDT Analysis

$m_{bb},\ p_{T,\gamma\gamma},\ \Delta R_{\gamma\gamma},\ p_{T,bb},\ \Delta R_{b_1\gamma_1},\ p_{T,\gamma_1},\ \Delta R_{bb},$
$p_{T,\gamma_2},\ \Delta R_{b_2\gamma_1},\ \Delta R_{b_2\gamma_2},\ p_{T,b_1},\ \Delta R_{b_1\gamma_2},\ p_{T,b_2},\ \not{E}_T,$

Signal Significance, $S/\sqrt{B}$ = 1.76

The other search channels

- $pp \to hh \to b\bar{b}\tau\tau$: $b\bar{b}\tau_h\tau_h$, $b\bar{b}\tau_h\tau_\ell$, $b\bar{b}\tau_\ell\tau_\ell$, dominant background is $t\bar{t}$.
    - Signal significance after BDT analysis: $\tau_h\tau_h = 0.74$, $\tau_h\tau_\ell = 0.49$, $\tau_\ell\tau_\ell = 0.08$.
- $pp \to hh \to b\bar{b}WW^*$: Semi-leptonic and fully leptonic channels, dominant background is $t\bar{t}$.
    - Signal significance after BDT analysis: leptonic = 0.62, semi-leptonic = 0.13.
- $pp \to hh \to WW^*\gamma\gamma$: Semi-leptonic and fully leptonic channels, dominant background is $t\bar{t}h$.
    - < 5 Signal events, S/B: leptonic = 0.40, semi-leptonic = 0.11.
- $pp \to hh \to WW^*WW^*$: 3 channels: (a) 2 lepton, (b) 3 lepton and (c) 4 lepton final states.
    - more lepton $\to$ low rate, more jets $\to$ lose cleanliness, signal significance < 1.
- Combined signal significance $\sim 2.1\sigma$ without any systematic uncertainty.

Di-Higgs production at HE-LHC

HE-LHC: 27 TeV @ 15 ab^{-1}, $\sigma(gg \to hh) = 139.9$ fb [CERN Twiki] .

7 di-Higgs final states are chosen:

- $b\bar{b}\gamma\gamma$
- $b\bar{b}\tau\tau \to \tau_h\tau_h$
- $b\bar{b}WW^* \to b\bar{b}ll + \not{E}_T$
- $WW^*\gamma\gamma \to ll\gamma\gamma + \not{E}_T$
- $b\bar{b}ZZ^* \to (a)\ b\bar{b}4l' + \not{E}_T$ and $(b)\ b\bar{b}2e2\mu + \not{E}_T$
- $b\bar{b}\mu\mu$

Multivariate analysis:

- Boosted Decision Tree (BDT) algorithm
- XGBoost toolkit
- Deep Neural Network (DNN)

The $b\bar{b}\gamma\gamma$ channel

Acceptance cuts
$N_{b\ jets} = 2,\ N_\gamma = 2$
$122\ \text{GeV} < m_{\gamma\gamma} < 128\ \text{GeV}$
$\Delta R_{b\gamma} > 0.2$
$m_{bb} > 50\ \text{GeV}$

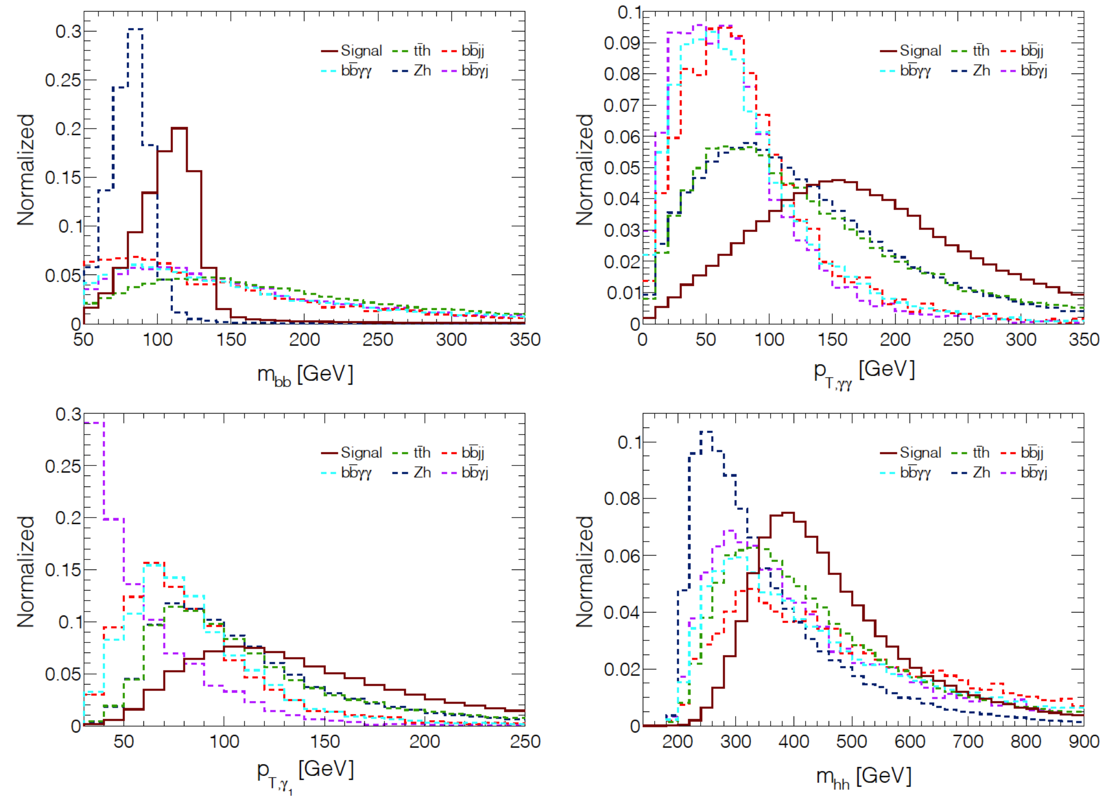


Fig. Normalised distributions of m_{bb}, $p_{T,\gamma\gamma}$, p_{T,γ_1}, m_{hh}.

Kinematic variables used:

$$m_{bb},\ \Delta R_{\gamma\gamma},\ \Delta R_{bb},\ p_{T,bb},\ p_{T,\gamma\gamma},\ \Delta R_{bb\ \gamma\gamma},\ p_{T,hh},\ \Delta R_{b_i\gamma_i},\ m_{hh},\ p_{T,b_{1,2}},\ p_{T,\gamma_{1,2}},\ \not{E}_T,\ \cos\theta^*,\ \cos\theta_{\gamma_1 h}$$

Result:

Signal significance, $S/\sqrt{B}$: BDT ~ 9.4 , DNN ~ 10 , XGBoost with 0 % (5%) systematics ~ 12.5 (5.1)

The other search channels

- $b\bar{b}\tau\tau$: Significance: BDT = 2.8, DNN = 4.3, XGBoost = 4.8 .
- $b\bar{b}WW^*$: Significance: BDT = 1.5, DNN = 1.4, XGBoost = 2.7, New kinematic variables used:

$$logT,\ logH,\ M_{T2}^{(b)},\ M_{T2}^{(\ell)},\ \sqrt{\hat{s}_{min}^{(\ell\ell)}},\ \sqrt{\hat{s}_{min}^{(bb\ell\ell)}},\ p_{T,\ell_{1/2}},\ \not{E}_T,\ m_{\ell\ell},\ m_{bb},\ \Delta R_{\ell\ell},\ \Delta R_{bb},\ p_{T,bb},\ p_{T,\ell\ell},\ \Delta\phi_{bb\,\ell\ell}.$$

- $WW^*\gamma\gamma$: Significance: BDT = 1.7, XGBoost = 2.1 .
- $b\bar{b}ZZ^*$: $t\bar{t}h$, Combined significance from both final states: BDT = 1.2, XGBoost = 1.4 .
- $b\bar{b}\mu\mu$: $t\bar{t}$, $b\bar{b}\mu\mu$, Significance < 1 .
- Combined significance $\sim 10\sigma$ (BDT), $\sim 14\sigma$ (XGBoost) without any systematic uncertainty.

Changing the Higgs self-coupling from SM

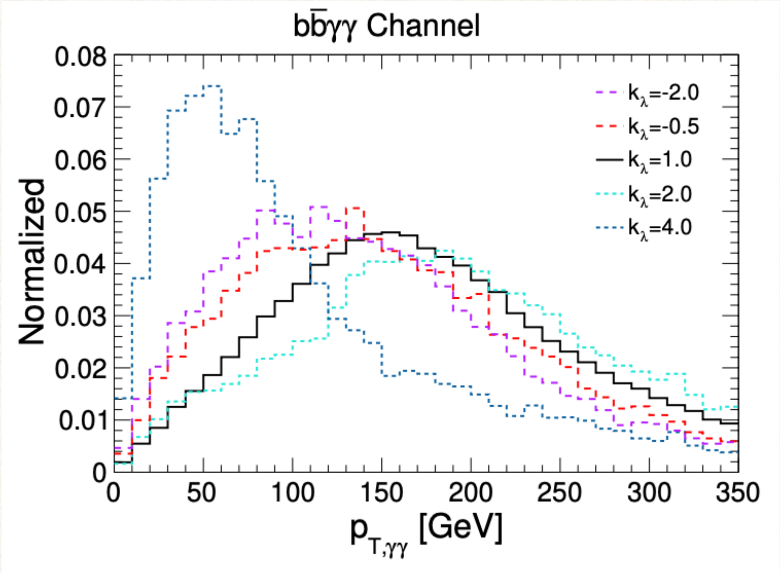


Fig. Normalised distribution of $p_{T,\gamma\gamma}$.

- Changing $\kappa_\lambda = \lambda/\lambda_{SM} \rightarrow$ modifies the kinematics of di-Higgs final state.
- Channels explored: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}WW^*$. The $\kappa_\lambda = 1$ optimisation is used.
- The HE-LHC would be sensitive to the entire range of $\kappa_\lambda = [-2,4]$.

Conclusion

- The prospect of observing Higgs pair production is bleak at the HL-LHC.
- Combining various di-Higgs search channels → better final result. We got signal significance $\sim 2.1\sigma$.
- HL-LHC → HE-LHC : di-Higgs production rate can improve by a factor of ~ 3.
- The HE-LHC can probe the Higgs self-coupling, with signal significance $> 10\sigma$.
- The HE-LHC will be sensitive in the range of Higgs self-coupling, $k_\lambda = [-2,4]$.

Thank you